Application of the Leslie Model to Commercial Catch and Effort of the Slipper Lobster, *Scyllarides squammosus*, Fishery in the Northwestern Hawaiian Islands

RAYMOND P. CLARKE and STACEY S. YOSHIMOTO

Introduction

Intensive fishing experiments are widely accepted in fishery literature as a relatively easy way to estimate the catchability coefficients of exploitable stocks. This information can be used to determine absolute estimates of exploitable stock, as compared with relative estimates (i.e., catch per unit effort (CPUE)). The two most widely accepted methods for obtaining these estimates are the Leslie and Delury models, which have been explored in considerable detail (Ricker, 1975; Crittenden, 1983; Schnute, 1983; Polovina, 1986). These models have several assumptions: The population fished is isolated or closed, fishing removals account for all changes in stock size, and catchability is constant (although as shown by Polovina (1986), this assumption is not restrictive). Substantial fishing effort exerted over a short timespan should reveal that the slope of a linear regression of CPUE on cumulative catch (Leslie and Davis, 1939) or LOG (CPUE) on LOG cumulative effort (Delury, 1947) is negative. In the Leslie model, the x-intercept reveals virgin stock size (K), the y-intercept shows initial CPUE at virgin biomass, and the absolute value of the slope of the line is the catchability coefficient (q).

Most of the reported studies using the Leslie model have involved laboratory experiments, fieldwork in ponds, or, more recently, field studies using research vessels at sea (Polovina, 1986; Ralston, 1986). While field studies offer many benefits, they may have operational and financial constraints resulting in relatively small amounts of effort being expended. One way to overcome this problem is to use commercial operations to fish marine reserves or restricted areas. If a commercial vessel fishes in a previously unexploited area for a reasonable amount of time, then removals from the fished stock will be great enough to cause a significant decline in CPUE. Such a situation presented itself in June 1986, when a commercial lobster vessel fished for slipper lobster, *Scyllarides squammosus*, at Laysan Island in the Northwestern Hawaiian Islands (NWHI). Laysan Island, with its associated bank, is a designated reserve for the spiny lobster, *Panulirus marginatus*, and had no prior history of slipper lobster exploitation. The vessel fished for 34 consecutive days and caught over 126,000 slipper lobster. As required by law, the vessel kept daily catch and effort logs for spiny lobster. The same data, along with additional information on trap placement, were maintained for slipper lobster. This otherwise confidential information was released by the vessel owner and skipper to the authors for analysis.

This paper presents a Leslie model modified for the use of commercial fisheries data to estimate catchability and preexploitation abundance of slipper lobster at Laysan Island. This species is distributed throughout the Indo-Pacific region north of Clipperton Island (Williams, 1986). A commercial slipper lobster fishery centered in the NWHI has recently emerged in conjunction with that for spiny lobster. In 1986, over 480 metric tons (t) of slipper lobster, valued at $2.3 million were landed by the NWHI lobster fleet (Clarke[1]). Until this time, estimates of catchability have been made by production models that treat spiny and slipper lobsters as one stock. Here, an independent estimate of slipper lobster alone will be presented, along with an estimate of preexploitation stock size at Laysan Island that may be applied to the entire NWHI lobster fishery.

Methods

The vessel fished between 11 June and 14 July 1986 in the vicinity of Laysan Island and its associated bank, which is

ABSTRACT—Commercial catch and effort data were fit to the Leslie model to estimate preexploitation abundance and the catchability coefficient of slipper lobster, Scyllarides squammosus, *in the Northwestern Hawaiian Islands (NWHI). A single vessel fished for 34 consecutive days in the vicinity of Laysan Island and caught 126,127 total slipper lobster in 36,170 trap hauls. Adjusted catch of legal slipper lobster dropped from a high of 3.70 to 1.16 lobster per trap haul. Preexploitation abundance at Laysan Island was an estimated 204,000 legal slipper lobster, which was extrapolated to yield an estimate of 1.2 × 10^6 to 3.8 × 10^6 lobster for the entire NWHI slipper lobster fishery.*

The authors are with the Honolulu Laboratory, Southwest Fisheries Center, National Marine Fisheries Service, NOAA, 2570 Dole Street, Honolulu, HI 96822-2396.

[1]Clarke, R. P. 1989. Annual report of the 1988 western Pacific lobster fishery. Honolulu Lab., Southwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96822-2396. Southwest Fish. Cent. Admin. Rep. H-89-5, 28 p.

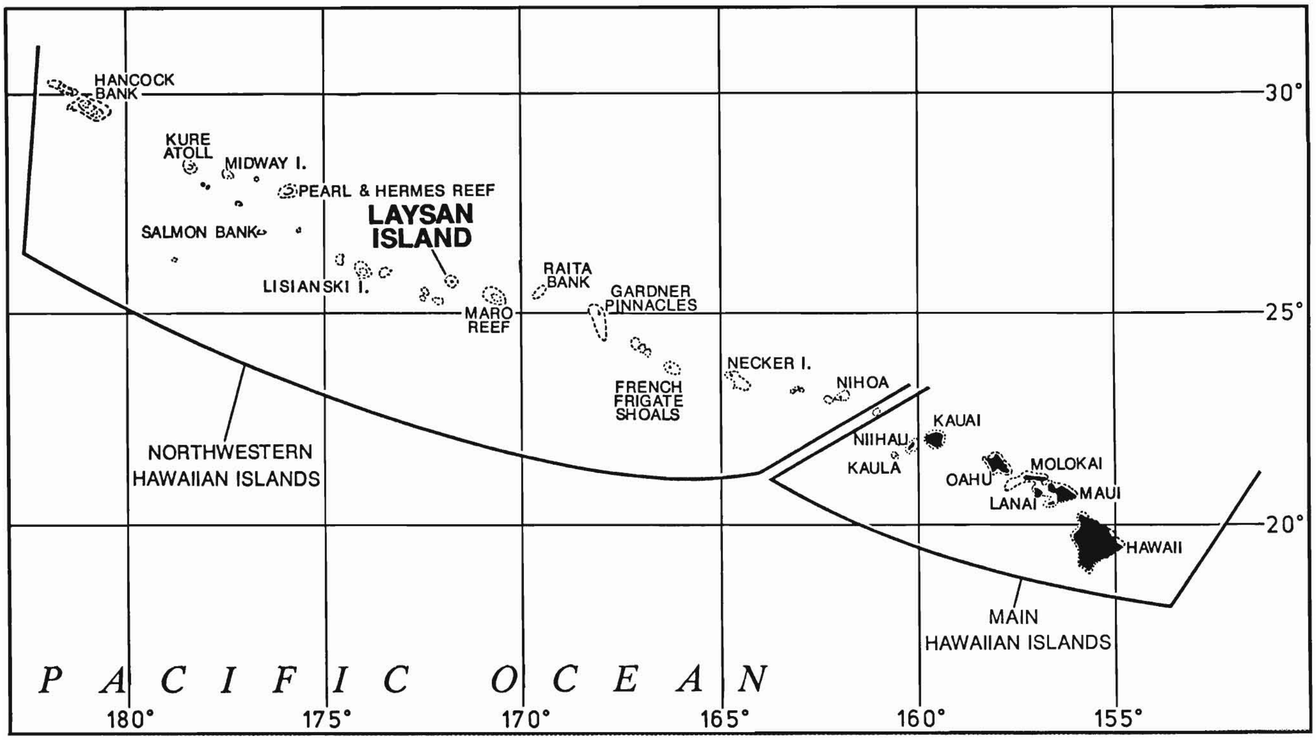

Figure 1.—The Northwestern Hawaiian Islands, including Laysan Island.

henceforth referred to as Laysan bank. Laysan Island is a small, uninhabited, predominantly coral-sand island, 2.8 km long and 1.7 km wide. It is located at lat. 25°42′N and long. 171°44′W, at the midpoint of the NWHI (Fig. 1), and is about 1,350 km northwest of Honolulu. The bank includes 482.2 km^2 (horizontal planar area) of potential habitat for lobster at the 20-200 m depths (WPRFMC[2]). Slipper lobster are known by NWHI fishermen to concentrate in areas at the 40-120 m depths.

The daily operations of the vessel involved deploying and hauling 1,125 Fathom Plus[3] lobster traps set in strings spaced at 30 m intervals. The traps are of black polyethylene construction (overall dimensions, 104 × 81 × 46 cm) and have two tapered entrance funnels (30 cm exterior diameter; 50 × 50 mm mesh). They were fished in 7 strings of about 160 traps each and baited with Pacific mackerel, *Scomber japonicus*. Strings were soaked overnight and retrieved the following day; therefore, the standard unit of effort is the trap-haul. The northwest corner of Laysan bank was initially explored for lobster concentrations at 30-120 m depths; however, some traps were set as deep as 200 m.

In 1986, there were no Federally mandated laws for slipper lobster. However, because of market conditions, the vessel retained only those slipper lobster that were free of eggs and had a tail size larger than 85 g (3 ounces), returning all others to the water. The vessel counted retained lobster but estimated the egg-bearing lobster and those below the 85 g minimum size. Since that time, a minimum size regulation of 56 mm tail width has been applied to the slipper lobster (WPRFMC[4]). The 56 mm tail width closely approximates the 85 g slipper lobster tail size (National Marine Fisheries Service (NMFS) unpubl. data); therefore, retained lobster can be viewed as legal lobster, those below 85 g as sublegal, and egg-bearing females as berried.

The general Leslie model is written as

$$U\langle t\rangle = q(K - CC\langle t\rangle); \qquad (1)$$

where $U\langle t\rangle$ is the CPUE at the time t, q is the catchability coefficient, K is preexploitation stock size, and $CC\langle t\rangle$ is the cumulative catch at time t. If slipper lobster are partitioned into legal, sub-

[2]Western Pacific Regional Fishery Management Council (WPRFMC). 1983. Spiny lobster fishery management plan. Western Pacific Regional Fishery Management Council, Honolulu, Hawaii, 213 p.

[3]Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

[4]Western Pacific Regional Fishery Management (WPRFMC). 1987. Crustacean fishery management plan amendment 5. Western Pacific Regional Fishery Management Council, Honolulu, Hawaii, 58 p.

Table 1.—Summary of catch and effort data from a commercial vessel fishing for slipper lobster at Laysan bank, Hawaii, 11 June through 14 July 1986. Legal lobster have tails ≥85 g, sublegal are <85 g, and berried are egg-bearing females. Catch per unit effort (CPUE) equals number of legal lobster per trap-haul.

Day	Lobster catch: Legal	Sublegal	Berried	Total	Adjusted cumulative legal catch	Daily effort	CPUE	Day	Lobster catch: Legal	Sublegal	Berried	Total	Adjusted cumulative legal catch	Daily effort	CPUE
1	2,133	1,000	1,000	4,133	1,066.5	1,125	1.896	19	2,362	425	260	3,047	51,393.0	1,125	2.099
2	1,675	450	600	2,725	2,970.5	1,125	1.488	20	2,142	400	300	2,842	53,645.0	1,125	1.904
3	2,976	1,785	1,050	5,811	5,296.0	1,125	2.645	21	1,955	290	235	2,480	55,693.5	1,125	1.737
4	3,788	1,850	1,580	7,218	8,678.0	1,125	3.367	22	1,924	210	135	2,269	57,633.0	1,125	1.710
5	2,883	1,750	1,150	5,783	12,013.5	1,125	2.562	23	2,332	320	280	2,932	59,761.0	1,125	2.072
6	2,430	1,470	980	4,880	14,670.0	1,125	2.160	24	1,216	145	205	1,566	61,535.0	645	1.885
7	4,092	2,400	1,600	8,092	17,931.0	1,125	3.637	25	2,158	235	150	2,543	63,222.0	1,125	1.918
8	3,267	1,800	1,200	6,267	21,610.5	1,125	2.904	26	2,328	380	230	2,938	65,465.0	1,125	2.069
9	3,440	1,000	1,500	5,940	24,964.0	1,125	3.057	27	2,612	575	210	3,397	67,935.0	1,125	2.321
10	2,790	820	450	4,060	28,079.0	1,125	2.480	28	2,332	480	245	3,057	70,407.0	1,125	2.072
11	2,418	740	500	3,658	30,683.0	1,125	2.149	29	2,605	545	310	3,460	72,785.5	1,125	2.315
12	2,112	420	300	2,832	32,948.0	1,125	1.877	30	2,312	510	210	3,032	75,334.0	1,125	2.055
13	2,325	340	150	2,815	35,166.5	805	2.888	31	2,046	325	290	2,661	77,513.0	1,125	1.818
14	2,325	320	190	2,835	37,491.5	805	2.888	32	2,280	385	250	2,915	79,676.0	1,125	2.026
15	2,976	450	325	3,751	40,142.0	805	3.696	33	2,523	387	268	3,178	82,077.5	1,125	2.242
16	2,232	360	380	2,972	42,746.0	805	2.772	34	1,308	175	95	1,578	83,993.0	1,125	1.162
17	2,670	380	340	3,390	45,197.0	805	3.316								
18	3,680	810	580	5,070	48,372.0	1,125	3.271	Total	84,647	23,932	17,548	126,127		36,170	

legal, and berried categories, equation (1) can be rewritten as

$$U_l + U_s + U_b = q_l(K_l - CC_l) + q_s(K_s - CC_s) + q_b(K_b - CC_b); \quad (2)$$

where the subscripts l, s, and b correspond to the legal, sublegal, and berried categories. During the intensive fishing at Laysan bank, sublegal and berried slipper lobster were returned after capture. To eliminate inaccuracies associated with the possibility of returned lobster being recaptured, only the legal terms in equation (1) were used:

$$U_l = q_l(K_l - CC_l) = \hat{U_l} - q_l(CC_l), \quad (3)$$

where $\hat{U_l}$ is the CPUE of legal slipper lobster at the preexploited stock size. By using ordinary least squares on equation (3), $\hat{U_l}$ and q_l can be estimated. Given that $\hat{U_l} = q_l K_l$, then K_l is estimated by dividing $\hat{U_l}$ by q_l.

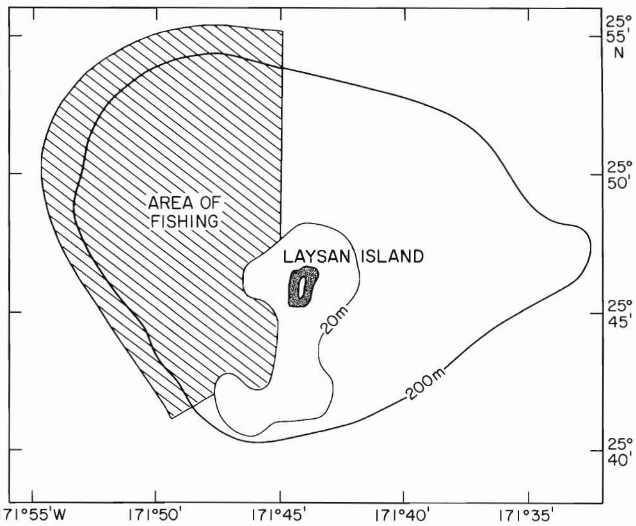

Figure 2.—Area of intensive slipper lobster fishing by a commercial lobster vessel on Laysan bank, Hawaii.

Results

Effort was concentrated in the northwest corner of Laysan bank but extended south to a sharp drop-off along the southern portion of the bank (Fig. 2). Normally the vessel set seven strings in the northwest corner at 30-200 m, but for a brief time (5 days), two strings (320 traps) were moved from the area to explore other potential fishing sites. Catches in these traps were poor and predominantly composed of spiny lobster, which were returned to the water; therefore, these traps and catches were eliminated from the totals. Catches along the northwest corner of the bank were almost all slipper lobster. About 126,000 total slipper lobster (all categories combined) were landed from 36,000 trap-hauls, yielding an overall CPUE of 2.34 legal (retained) and 3.487 total slipper lobster per trap-haul (Table 1).

The CPUE data for legal slipper lobster were fit to the Leslie model (Ricker, 1975). The CPUE was calculated on a catch per trap-haul basis and regressed against the adjusted cumulative catch (Fig. 3), which was the cumulative catch at the start of a fishing day plus half of the catch taken during that day (von Geldern, 1961). The slope of the predicted line

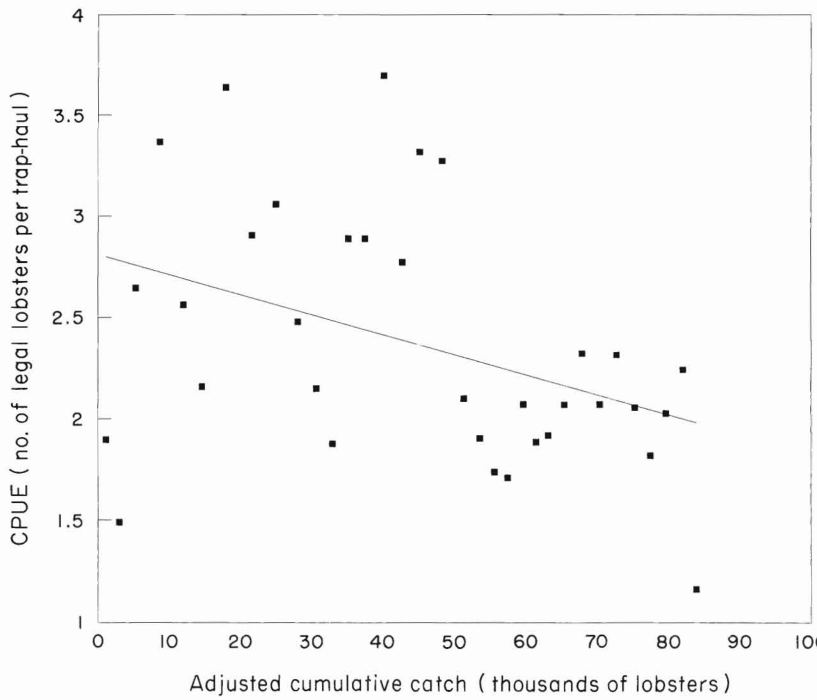

Figure 3.—Leslie model applied to the intensive fishing experiment for slipper lobster at Laysan bank, Hawaii. Each point represents 1 day of fishing. Data are from Table 1.

depicted in Figure 3 was significantly less than zero (one-tailed t-test, $P = 0.01$; $t = -2.45$; df = 32); however, the Durbin-Watson statistic (1.12) indicated autocorrelation problems, which could bias parameter estimates. By applying the Cochrane-Orcutt procedure (Wittink, 1988), the problem was corrected (DW = 2.04); the slope of the corrected line was significantly less than zero (one-tailed t-test, $P = 0.05$; $t = -2.25$; df = 32). The slope of the corrected line is -1.52×10^{-5} (SD = 6.76×10^{-6}), and the y-intercept is 3.10 (SD = 0.204). Therefore, the catchability coefficient is an estimated 1.52×10^{-5} trap-haul^{-1}, and the initial stock size is 204,000 slipper lobster with tails of 85 g or greater [confidence intervals: $P(7.49 \times 10^{-6} < q < 1.22 \times 10^{-5}) = 0.95$ and $P(181{,}945 < K < 970{,}786 = 0.95$, respectively]. An estimate of CPUE at virgin biomass is 3.10 [confidence interval: $P(2.68 < u_K < 2.94) = 0.95$].

As suggested by several previous investigators, the possibility of heteroscedasticity in the plot of CPUE against adjusted cumulative catch was explored by using the Goldfeld-Quandt test in Wittink (1988). A regression of CPUE on adjusted cumulative catch revealed that the sample variance (S) for the first 14 fishing days ($S^2{}_1 = 0.417$) and the last 14 fishing days ($S^2{}_2 = 0.105$) indicated no evidence of heteroscedasticity ($S^2{}_2/S^2{}_1 < F_{12,\,12}$ at 0.05). In addition, a runs test on the signs of the residuals indicated they were randomly sequenced ($P > 0.50$). The effects of the lunar cycle were tested by using a dummy variable and found not to be statistically significant ($P = 0.05$).

Discussion and Extrapolation of Results

The commercial data presented appear to give reasonable results; however, initially it may be appropriate to consider whether any of the basic assumptions of the Leslie model were violated. The initial assumption of an isolated population is evident by the geographical features of Laysan bank, which rises out of several thousand meters of water. Although the recruitment pattern of spiny lobster larvae in the NWHI is believed to be regionwide (MacDonald, 1986), there is no evidence to support postsettlement migration between banks by any species of lobster. Bathymetric charts of the fishing area show a sharp drop-off on the southwestern corner of the bank that may act as an additional physical barrier to substantial immigration to or emigration from other parts of the bank during the fishing period. Anecdotal information from experienced lobster fishermen indicates that steep drop-off areas are not normally conducive to large concentrations of lobster, but slipper lobster may be present. The northern extent of trapping does not show as good a physical boundary as in the south, but no trap strings were fished east of lat. 171°45′W, except those eliminated as exploratory. Therefore, we believe our initial assumption was fulfilled during the experiment.

The second assumption that changes in population stock size were due only to fishing mortality is more difficult to prove, though there is little evidence to the contrary. The fishing period was relatively short; however, one cannot rule out the possibility that recruitment to the fishery may have occurred or that mortality was abnormal. Little information presently exists on the molting and recruitment patterns of slipper lobster. The time from their settlement as pueruli to recruitment to the fishery is estimated at 3.3 years (Polovina and Moffitt[5]), of which the 34-day fishing period represents a small (2.8 percent) proportion. No data exist on the proportion of the population undergoing molting, which may alter their foraging behavior and thus the probability of capture by baited traps. In other lobster species, these changes can cause corresponding changes in the catchability coefficients (Morgan, 1974; Newman and Pollock, 1974). Our data

[5]Polovina, J. J., and R. B. Moffitt. 1989. Status of lobster stocks in the Northwestern Hawaiian Islands, 1988. Honolulu Lab., Southwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96822-2396. Southwest Fish. Cent. Admin. Rep. H-89-3, 10 p.

and statistical analysis indicate that q, the catchability coefficient, was constant during the exploitation at Laysan bank. Without any evidence to the contrary, we believe that the third assumption (i.e., catchability was constant) has not been violated. It would have been useful for the vessel to have returned later to the bank and fished the area again to determine whether the slipper lobster CPUE stayed depressed, but this did not occur. In addition, no length-frequency information was taken, so conclusions as to shifts in size classes cannot be made.

The fact that the data had to be corrected for autocorrelation can be explained by the fishing patterns of the vessel. While the strings were moved each day, the success on any one day clearly had an effect on where the traps were set the following day, and as CPUE levels dropped, the vessel changed its pattern of fishing altogether. Daily plots of trap string locations reveal the vessel initially fished perpendicular to the depth contours of the bank, but as CPUE dropped, the vessel apparently began to set strings parallel to the depth contours at 60-120 m to better target optimal fishing areas.

Table 2.—Estimated total catch per unit effort (CPUE; number of lobster per trap-haul) and stock size of slipper lobster in the lobster fishery in the Northwestern Hawaiian Islands, 1985-86[1]. NF = no fishing.

Location	CPUE 1985	CPUE 1986	Area[2] (km^2)	Stock (No.) 1985	Stock (No.) 1986
Nihoa	NF	1.04	124.8		17,708
Necker Island	0.83	0.40	1,913.2	216,654	104,412
French Frigate Shoals	0.41	0.39	538.8	30,140	28,670
Brooks Banks	1.84	1.50	406.2	101,973	83,130
St. Rogatien	0.91	0.66	476.4	59,148	42,899
Gardner Pinnacles	1.46	0.56	3,000.4	597,670	229,243
Raita	0.52	0.73	697.9	49,514	69,510
Maro Reef	1.63	1.04	1,887.6	419,785	267,838
Pearl and Hermes Reef	0.75	NF	426.7	43,663	
Kure Atoll	0.48	NF	66.0	4,323	
Lisianski Island	0.66	1.77	922.2	83,042	222,704
Midway	0.35	NF	268.4	12,817	
Other[3]		2.47	1,947.0		656,133
Total				1,618,729	1,722,247

[1]Clarke, R. P., S. G. Pooley, P. A. Milone, and H. E. Witham. 1988. Annual report of the 1987 western Pacific lobster fishery. Honolulu Lab., Southwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96822-2396. Southwest Fish. Cent. Admin. Rep. H-88-5, 48 p.
[2]From text footnote 2.
[3]Includes Northampton Seamount, Pioneer Bank, Pearl and Hermes Reef, Midway, Kure Atoll, an unnamed bank north of St. Rogatien, and Laysan bank.

Many studies using intensive fishing experiments do so with the intent of determining absolute estimates of stock size over a given unit of area (square kilometer of habitat or linear kilometer of appropriate depth contour; Polovina, 1986; Ralston, 1986; von Geldern, 1961). The same exercise was attempted for the NWHI slipper lobster population, revealing surprising results. Lobster density determined on the west and northwest portion of Laysan bank was taken as a minimum estimate of unexploited stock size for the entire bank. We believe it is inappropriate to extrapolate this density over the entire area of the bank, given the reportedly poor catches for the exploratory strings set on the other side of the bank. The NMFS lobster assessment research data from 1985 and 1986 (NMFS unpubl. data) confirm that catch rates for slipper lobster by black plastic traps were greatest in the northwest corner of the bank and diminished substantially toward the southeast portion. Therefore, for this exercise, we have applied the absolute abundance in the area fished to the entire bank.

Assuming the density estimate from Laysan bank (K/482.2 km^2) is an appropriate indicator of the potential number per square kilometer (422 slipper lobster/km^2 at the 20-200 m depths), the entire NWHI (8,876 km^2 of potential habitat at the 20-200 m depths) would have 3.75 million legal slipper lobster. Previous estimates of K for the entire NWHI equaled 3-4 million legal spiny and slipper lobsters combined (Polovina, 1989). Fishery catch totals for spiny lobster were equal to or greater than those of slipper lobster during 1985-88. This method of assuming an even distribution of slipper lobster over the entire potential area yields results that are twice the previous estimates. Slipper lobster at Laysan bank apparently were concentrated on the northwest corner of Laysan bank for some unknown reason, and an alternative method of extrapolation was necessary to account for this patchiness.

The alternative method assumes that slipper lobster distribution varies from bank to bank in the NWHI. The only measure of relative abundance for all the banks fished is from commercial catch and effort data collected during the initial years (1985-86) of slipper lobster exploitation; however, as will be discussed later, these data have limitations also. The estimate of catchability coefficient for Laysan bank was applied to obtain bank-specific densities for those areas reported as being fished. These values were multiplied by the bank's horizontal planar area relative to Laysan bank (Table 2). The CPUE data represent total slipper lobster caught; therefore, the estimates were adjusted by the same factor as that seen at Laysan bank to exclude sublegal and berried lobster.

The resulting estimates of stock size appear questionable even when adjusted for catches of sublegal and berried slipper lobster. In the NWHI, a total of 1.19 million slipper lobster were reported caught in 1985 and 1.24 million in 1986. Adjusting these catches by eliminating the sublegal and berried lobster shows that 74 percent (797,194 legal slipper lobster) of the estimated stock were landed in 1985 and 72 percent (829,143 legal slipper lobsters) in 1986. The value of K is underestimated by this method, because CPUE values are reported without targeting information and represent a composite of the fishing effort for spiny and slipper lobsters. Information on the targeting practices of the fishermen is not available; therefore, effort segregation is impossible.

The data show that after day 13 of in-

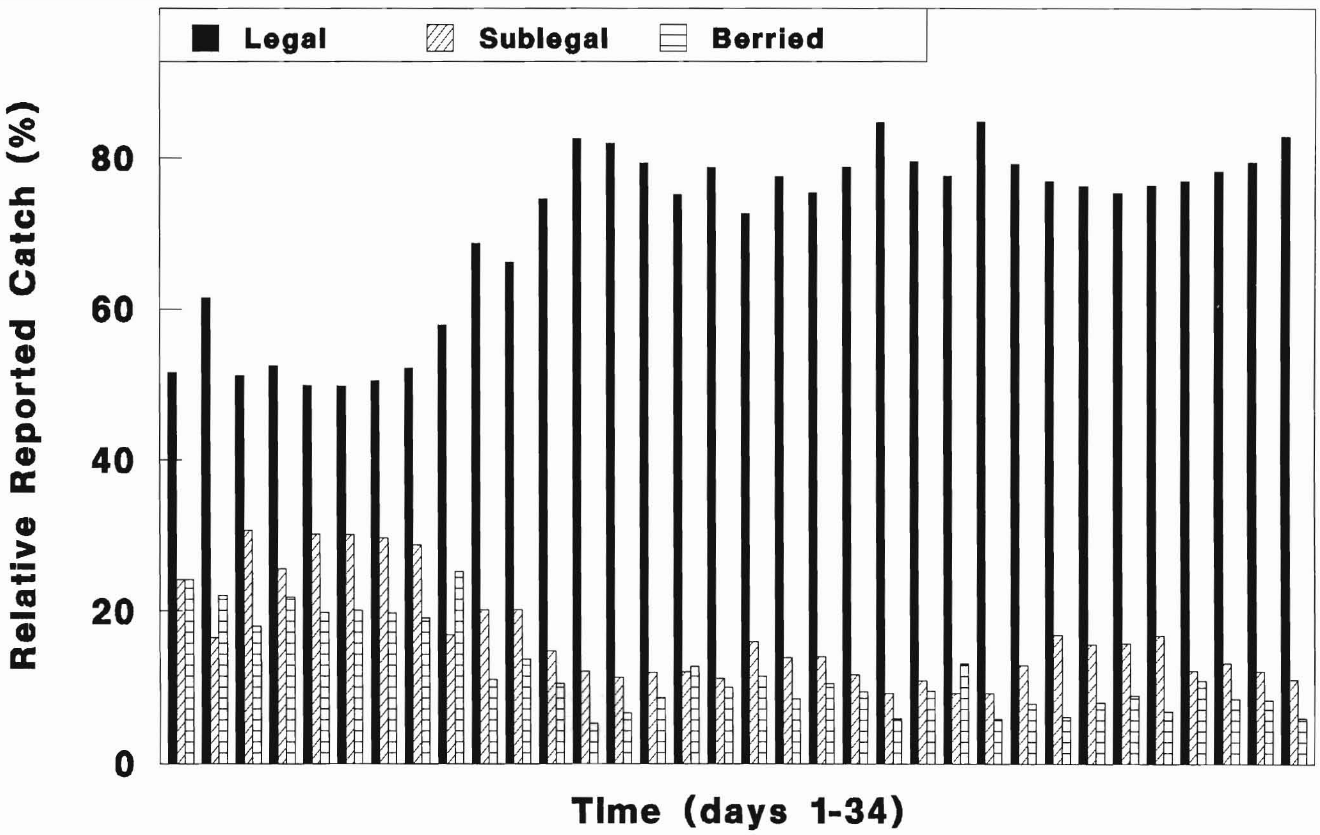

Figure 4.—Relative breakdown of reported catch categories (legal lobster have tails ≥85 g, sublegals have tails <85 g, and berried are egg-bearing females) at Laysan bank, Hawaii, 1986.

tensive fishing at Laysan bank, the relative proportion of legal, sublegal, and berried slipper lobster stabilized (Fig. 4). Prior to that period, the percentages of berried and sublegal lobster were greater, indicating that berried females may have been releasing their eggs and becoming part of the retainable (legal) pool of lobster. However, the same trend is seen for sublegal lobster. This potential problem was cleared up in discussions with the skipper of the vessel, who indicated that numbers of berried and sublegal lobster were to be taken as estimates only and reflected estimating errors during the initial period of fishing, which was heavy even by commercial standards. As the slipper lobster CPUE declined, fishing returned to levels normally experienced by the vessel and allowed time to better estimate the numbers of sublegal and berried lobster returned to the water.

Conclusion

The use of the commercial data appears not to substantially violate any of the underlying assumptions of the Leslie model. The commercial catch data from Laysan bank produce reasonable estimates of K and q, but fishery-wide extrapolations yield estimates that are different than those presently accepted. Our results indicate that present estimates of K are probably low, and the true value probably lies somewhere between the two estimates presented here. Using two accepted methods of extrapolation, the low estimate for slipper lobster unexploited abundance is 1.2×10^6 legal slipper lobster, and the high is 3.8×10^6, yielding a mean of 2.5×10^6.

The catch data indicate that slipper lobster are extremely vulnerable to trapping, especially when concentrated in the proportions seen at Laysan bank. Catch and effort logs show fishermen have the ability to effectively target slipper lobster. Research directed at the causes of these concentrations is necessary, and if they are found to be related to some biological or behavioral phenomena and if present regulations are unable to sustain sufficient spawning stock biomass, a seasonal closure may be warranted for the slipper lobster fishery in the NWHI.

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